An Effect of the Eccentric Position of the Propeller Agitator on the Mixing Time*

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An effect of the eccentric position of the propeller agitator on the mixing time was studied. The case of the upward and downward pumping mode of the single and double propeller agitators, located eccentrically in the 0.27 m^3 cylindrical vessel was analyzed. Tracer experiments were used to determine the mixing time. Measurements were conducted within the turbulent regime of the Newtonian liquid flow in agitated vessel.

In comparison with the data obtained for the centric position of the propeller, mixing time decreases with the increase of the eccentricity and number of the impellers. Pumping mode of the propeller affects also the mixing time, especially when the liquid is agitated by means of the impeller located in the centric position in the agitated vessel. The results of the dimensionless mixing time Θ, obtained within the range of the performed measurements, are described mathematically (eqns (*1*) and (*2*)).

Agitated vessels are often used for homogenization of the miscible liquids in chemical, biochemical, and food industries [1, 2]. Recently, many aspects concerning the liquid homogenization in the vessels with centrally located agitators have been analyzed in detail [3—6]. *Rieger* and *Rzyski* [3] proposed a criterion for the efficiency estimation of different agitators used to homogenize the viscous liquids. The effects of the amount of the liquid added as a tracer and the location of the point of the tracer pulse on the mixing time were analyzed by *Gogate* and *Pandit* [4] and *Patil et al.* [5], respectively. Mixing time in a baffled agitated vessel with double impeller system was studied by *Hiraoka et al.* [6].

Unbaffled agitated vessels with eccentrically located agitator shaft can be used instead of the baffled vessels when, for example, the liquids with higher viscosity or suspensions are agitated [1, 2]. The eccentric position of the agitator in the vessel improves mixing time [7—9]. In such case, mixing is more intensive than in the unbaffled vessel, but higher agitation energy must be provided to the system. The effect of the shaft eccentricity e/R on the power consumption was studied and described previously [7, 8, 10—12]. *Medek* and *Fort* [11] analyzed experimentally the influence of nonstandard baffles in the vessel on the power consumption and pumping capacity of the eccentric agitator. *King* and *Muskett* [12] investigated the effect of the distance between vessel bottom and eccentric agitator on the power consumption. *Karcz* and *Cudak* [13, 14] studied heat transfer in a jacketed agitated vessel with eccentrically located propeller or HE 3 impeller. Improvement of the heat transfer effectiveness was observed in comparison with the results obtained for unbaffled vessel with centrally located agitator.

In this study an effect of the eccentric position of the propeller agitator on the mixing time is presented. The case of the upward and downward pumping mode of the single and double propeller agitators, located eccentrically in the cylindrical vessel with the liquid volume of 0.27 m^3, was analyzed. Additionally, an effect of the position of the measuring sensor in the agitated vessel on the value of the mixing time was investigated. These aspects of the studies on mixing time have not been described in literature yet.

EXPERIMENTAL

Measurements of the mixing time were carried out in an agitated vessel without baffles. The vessel of inner diameter D = 0.7 m was filled with Newtonian liquid up to the height $H = D$, thus, the volume of liquid in the vessel was 0.27 m^3. Single ($i = 1$) or double ($i = 2$) propeller agitators of diameter $d = 0.33\ D$ were located in the agitated vessel vertically at the centric or eccentric positions (Fig. 1). Off-bottom clearance of the lower and upper agitators were h_1 = 0.33 H and h_2 = 0.67 H, respectively.

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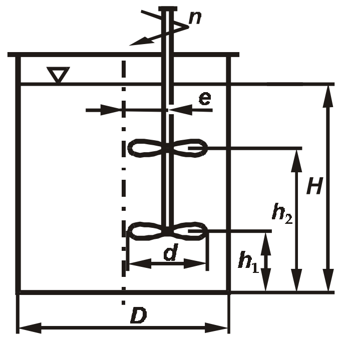

Fig. 1. Eccentric position of the impeller shaft in the vessel; $e/R \neq 0$.

Three-blade ($Z = 3$) propellers with the pitch $S = d$ were used to agitate the liquid. Eccentricity of the agitator, described by means of the parameter e, was varied within the range of $e/R \in \langle 0; 0.57 \rangle$, where $R = D/2$ denotes the radius of the agitated vessel.

Tracer experiments were used to determine the mixing time τ_{m}. The measurements were carried out by means of the thermal method. In each experiment, two tracer dosage points with radial coordinate $r/R = 0.71$ and angular coordinates $\varphi_{\mathrm{IP1}} = 200°$ and $\varphi_{\mathrm{IP2}} = 340°$, respectively, were assumed (Fig. 2). The pulse injection of the tracer was done onto the liquid surface. The system response was measured at twelve points with different radial (r_1, r_2, and r_3) and angular ($\varphi = 0°$, 90°, 180°, and 270°) coordinates at a given axial coordinate $z = 0.2$ m under the liquid level in the vessel (Fig. 2).

An effect of the up- and down-pumping mode of the eccentrically located propeller agitator on the mixing time was analyzed experimentally. In total, eight series of measurements were conducted for the single or double propellers, up- or down-pumping mode of both agitator systems and for the two points of the tracer dosage. Aqueous solution of molasses with viscosity of 2.5×10^{-3} Pa s was agitated at 20 °C within the turbulent regime of the liquid flow in the agitated vessel.

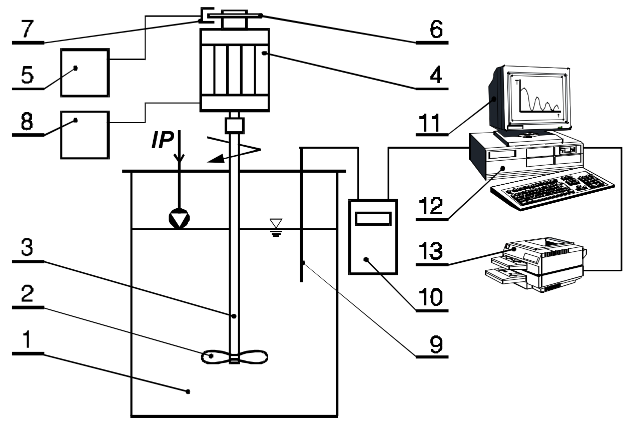

Fig. 3. Experimental set-up: *1.* agitated vessel; *2.* agitator; *3.* agitator shaft; *4.* electric motor; *5.* electronic counter of the agitator speed; *6.* perforated disc; *7.* photoelectric sensor; *8.* steering unit; *9.* measuring probe; *10.* digital converter of temperature; *11.* monitor; *12.* computer; *13.* printer.

Mixing time was determined by means of the thermal method using a computer-aided experimental set-up shown in Fig. 3. After injection of a small amount, V_{a}, of tracer into the agitated liquid, temperature change was measured at a given point of the liquid volume by a temperature probe. Molasses heated up to 90 °C was used as a tracer. Temperature probe with contact tip made of platinum was an integral part of the digital conductometer CC-317 produced by ELMETRON. The conductometer, operating in the option of the temperature measurement, was coupled with a computer PC. Sampling of the temperature was carried out automatically with the period of 1 s. The results were stored in and processed using spe-

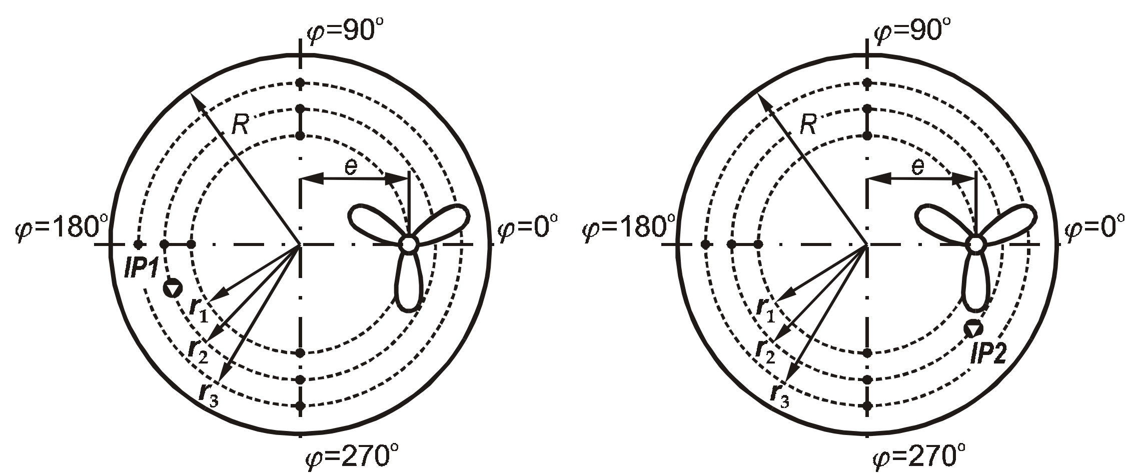

Fig. 2. Position of measurement (r_1, r_2, r_3 and $\varphi = 0°$, 90°, 180°, and 270° at $z = 0.2$ m) and tracer dosage ($r/R = 0.71$, $\varphi_{\mathrm{IP1}} = 200°$ and $\varphi_{\mathrm{IP2}} = 340°$ at $z = 0$ m) points within the agitated vessel.

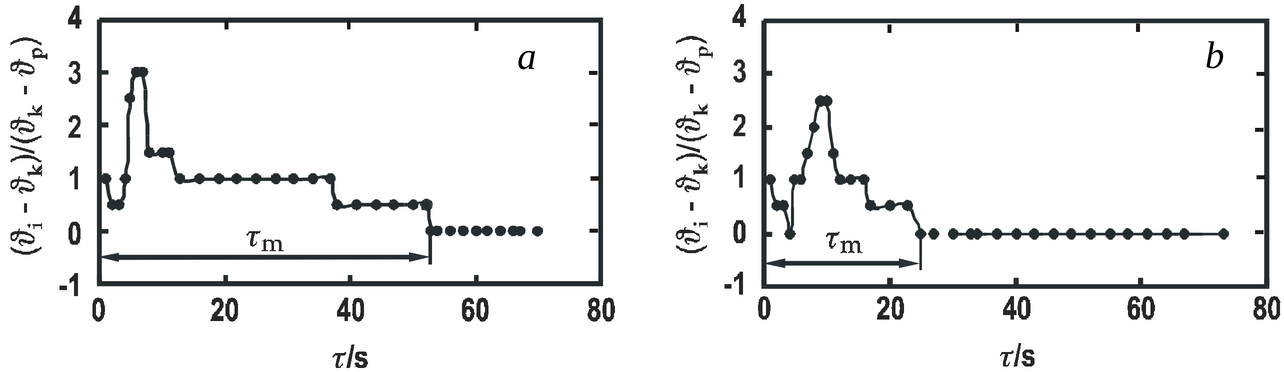

Fig. 4. Variation of dimensionless temperature with time for centric (a) $e/R = 0$) and eccentric (b) $e/R = 0.43$) position of the up-pumping propeller, IP1, $Re = 42000$.

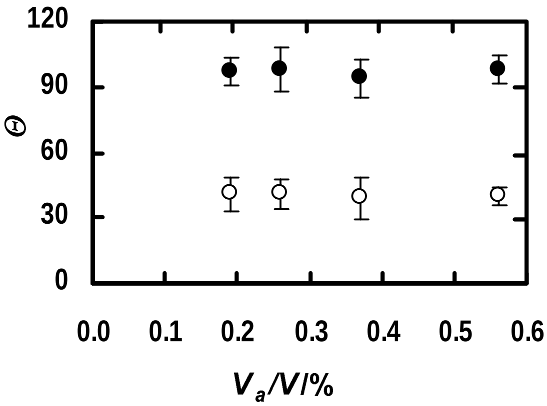

Fig. 5. The effect of the tracer volume on the dimensionless mixing time for single up-pumping propeller, IP1, $Re = 42000$, and the agitator shaft eccentricity $e/R = 0$ (●) or $e/R = 0.43$ (○).

cial software. During a given experiment, difference of the liquid temperature varied locally within the limits 1—1.5 ℃ at the start of the measurement.

The temperature fluctuations with time for both, centric and eccentric positions of the propeller in the vessel are illustrated in Fig. 4. Dimensionless temperature was defined as $(\vartheta_i - \vartheta_k)/(\vartheta_k - \vartheta_p)$, where ϑ_p, ϑ_k, and ϑ_i is the temperature at the time τ_p, τ_k, and τ_i, respectively (τ_p, τ_k – time, at which the experiment is started and stopped, respectively; $\tau_i \in \langle \tau_p; \tau_k \rangle$). As the mixing time, τ_m, the time required for 95 % liquid homogenization was assumed.

An effect of the tracer volume V_a on the mixing time τ_m was tested during preliminary study, for a given $Re = 42000$, within the range of the $V_a/V \in \langle 0.18\ \%; 0.56\ \% \rangle$, where V is the liquid volume in the vessel. Experimental results showed that the dimensionless mixing time Θ did not depend on the tracer volume injected into the vessel for both centric and eccentric position of the up-pumping single propeller (Fig. 5). Therefore, tracer volume $V_a = 2.6 \times 10^{-3}\ V$ was chosen for the further series of experiments.

RESULTS AND DISCUSSION

About 700 experimental data of mixing time τ_m were collected for agitated vessel equipped with centrally ($e/R = 0$) or eccentrically ($e/R \in \langle 0; 0.57 \rangle$) located propeller agitator within the turbulent regime of the Newtonian liquid flow ($Re \in \langle 2 \times 10^4; 1 \times 10^5 \rangle$). The data include the results for single ($i = 1$) or double ($i = 2$) propellers working at the up- or down-pumping mode, and for the two tracer injection points (IP1 or IP2).

Values of the mixing time τ_m measured at different positions by the temperature probe are shown in Fig. 6 for several geometrical configurations of the agitated vessel. In general, the value of τ_m measured at chosen sensor positions did not vary substantially when the axial symmetry of the system was maintained (Figs. 6a, 6b). Opposite behaviour, variation of the mixing time with the measuring probe position in the vessel was observed in the case of eccentrically located agitator (Fig. 6c). Comparison of the data in Fig. 6, for assumed Re number and injection point ($Re = 42000$; IP1), shows that the longest mixing times τ_m were found for central position of the shaft ($e/R = 0$). These results were obtained for up-pumping single propeller in the agitated vessel without baffles ($e/R = 0$; $i = 1$, Fig. 6a). By changing the liquid circulation in the vessel using the down-pumping mode, the mixing time τ_m decreased (*cf.* Figs. 6a, 6b with Figs. 6d, 6e). Mixing time decrease was also observed when the shaft eccentricity e/R (see Figs. 6a, 6c and Figs. 6d, 6f), as well as the number of agitators on the common shaft (Figs. 6a, 6d and Figs. 6b, 6e) was increased.

Dimensionless time $\Theta = n\tau_m$ with confidence intervals, calculated as a mean value of twelve measurements at different points of the cross-section area, is compared in Table 1 for various eccentricities e/R and given Re number ($Re = 42000$). In the case of the tracer injection onto the liquid surface, the position of the dosage point (IP1 or IP2) did not affect the dimensionless mixing time Θ when single and dou-

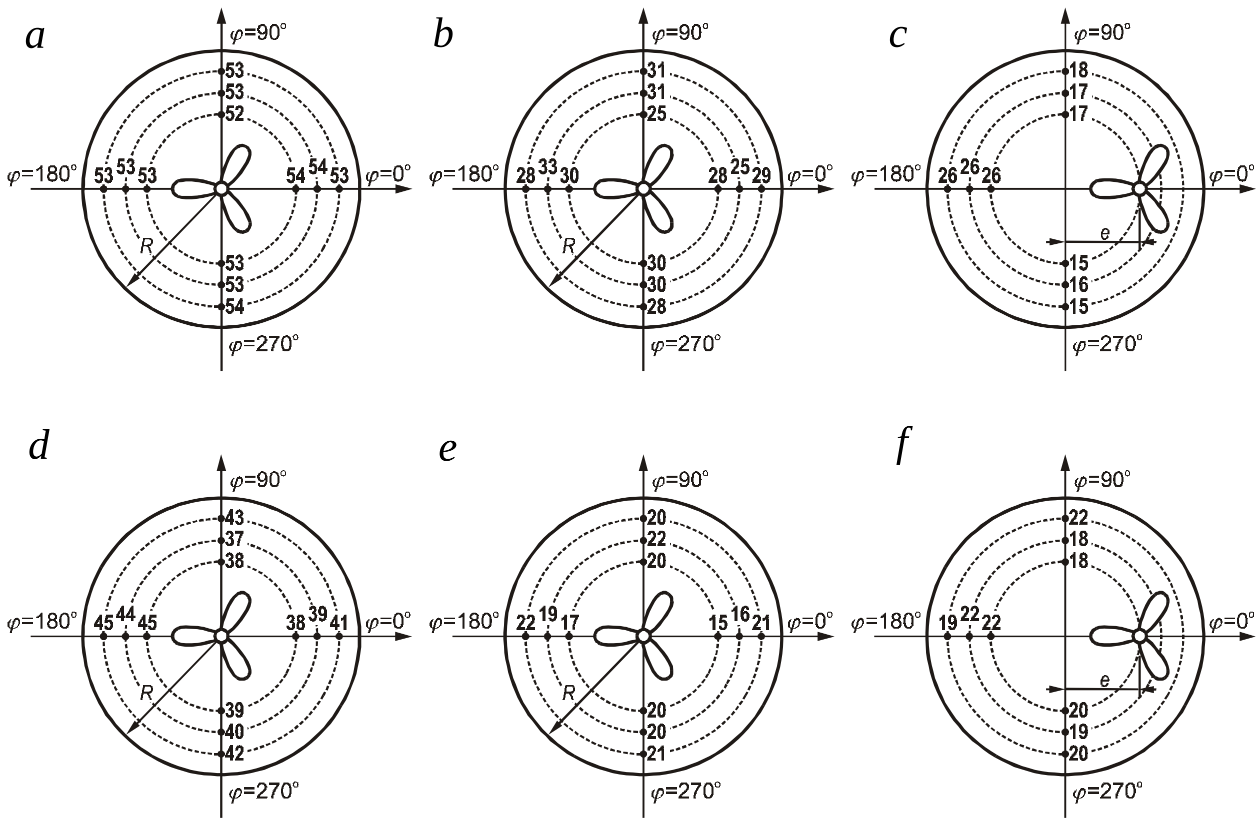

Fig. 6. Mixing time τ_m measured at $Re = 42000$, IP1, for different experimental conditions: *a*) P↑, $i = 1$, $e/R = 0$, *b*) P↓, $i = 1$, $e/R = 0$, *c*) P↑, $i = 1$, $e/R = 0.57$, *d*) P↑, $i = 2$, $e/R = 0$, *e*) P↓, $i = 2$, $e/R = 0$, and *f*) P↑, $i = 2$, $e/R = 0.57$.

Table 1. Averaged Dimensionless Mixing Time Θ and its Standard Deviation for Varied Eccentricity of the Agitator Shaft e/R and Different Combinations of Pumping Modes (Up- ↑ and Downwards ↓) of Single ($i = 1$) and Double ($i = 2$) Propellers and the Tracer Dosage Position (IP1 or IP2) for $Re = 42000$

e/R	$i = 1$				$i = 2$			
	P↑, IP1	P↑, IP2	P↓, IP1	P↓, IP2	P↑, IP1	P↑, IP2	P↓, IP1	P↓, IP2
0	87 ± 5	89 ± 5	53 ± 10	41 ± 25	72 ± 11	61 ± 11	33 ± 9	30 ± 9
0.14	65 ± 24	62 ± 24	41 ± 12	42 ± 26	55 ± 13	48 ± 18	32 ± 7	27 ± 10
0.29	83 ± 33	77 ± 29	38 ± 13	43 ± 18	34 ± 8	30 ± 7	37 ± 6	33 ± 8
0.43	33 ± 4	41 ± 6	37 ± 11	38 ± 17	33 ± 16	36 ± 12	37 ± 5	30 ± 13
0.57	32 ± 19	44 ± 13	34 ± 9	43 ± 13	29 ± 6	27 ± 8	37 ± 7	22 ± 5

ble propellers were located centrally. In comparison with the data observed for IP1, higher mean value of Θ_m was obtained for the second tracer injection position, IP2, in the vessel with eccentrically located single propeller ($e/R = 0.43$ or 0.57) independently of the pumping mode of the agitator. However, the confidence intervals for the data obtained when dosing the tracer at the positions IP1 and IP2 were overlapped. In the vessel agitated with eccentrically located double down-pumping propeller, lower mean values of Θ were obtained for the point IP2 of the tracer dosage.

Dimensionless time decreases with the increase of the shaft eccentricity e/R, as shown in Table 1. Comparing with the data for centric position ($e/R = 0$), the value of Θ is lower by about 60 % and 30 %, respectively, for the up- and down-pumping mode of the single agitator, eccentricity $e/R \in \langle 0.43; 0.57 \rangle$, and the dosing point IP1. Analogous comparison shows that dimensionless time decreases by about 50 % in the vessel with eccentrically located double up-pumping propeller.

The data collected in Table 1 reveal a significant effect of the agitator pumping mode on the mixing time. Independently of the number of the agitators on the common shaft, the shorter mixing times were reached when the propeller imposed the liquid circulation to the bottom of the vessel (down-pumping mode of the agitator). The highest differences were observed in the

Table 2. Values of Parameters C and A and Mean Relative Error for Experimental Data Fit by Eqns (*1*) and (*2*) Obtained for Selected Experimental Conditions

C	A	e/R	i	$Re \cdot 10^{-4}$	IP	Pumping mode	Δ/%
92	0	0	1	2—7.5	1, 2	P↑	± 7
48	0	0	1	2—7.0	1	P↓	± 8
72	0	0	2	2.5—10	1	P↑	± 7
38	0	0	2	3—7	1, 2	P↓	± 5
1.019	0.35	$\langle 0.43; 0.57\rangle$	1	2.5—9	1	P↑; P↓	± 10
1.79	0.30	$\langle 0.43; 0.57\rangle$	2	2.5—9	1	P↑; P↓	± 8

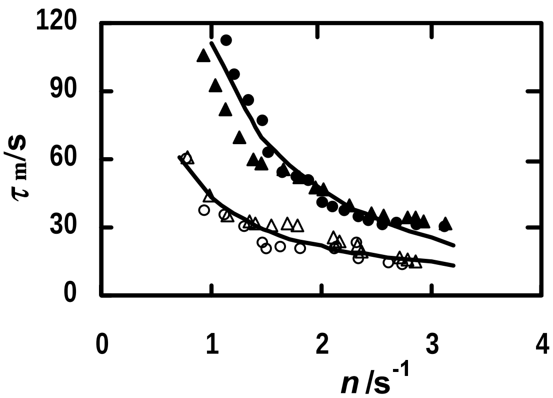

Fig. 7. Variation of the mixing time with the agitator speed for centrally located up- (filled symbols), or down-pumping (empty symbols) single propeller agitator. Experimental data obtained for tracer liquid injection at IP1 (triangles) and IP2 (circles). Solid lines indicate trends of the data.

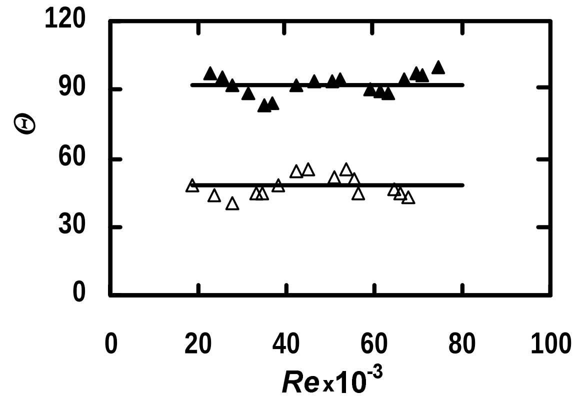

Fig. 8. Influence of the liquid turbulence on the dimensionless mixing time for centrally located up- (▲) and down-pumping (△) single propeller agitator.

agitated vessel with centrally located propeller ($i = 1$ or $i = 2$) when the values of Θ for down-pumping agitators were about 65 % ($i = 1$) and 45 % ($i = 2$) of the values measured for the up-pumping propellers. The effect of the agitator pumping mode on the mixing time decreased with the increase of the shaft eccentricity in the vessel, for both single and double propellers.

Second propeller agitator on the common shaft improved axial circulation of the liquid in the vessel thus shortening the mixing time (Table 1), especially for the central position of the agitator shaft in the vessel ($e/R = 0$).

The highest value from within the set of mixing time values measured at the twelve different positions was chosen for further calculations. Variation of the mixing time τ_m with the agitator speed n is shown in Fig. 7 for the vessel agitated with centrally located up- and down-pumping single propeller. Solid lines in Fig. 7 indicate trends of the experimental data. For both positions of the tracer dosage, the mixing time τ_m was significantly shortened by increasing the agitator speed n, *i.e.* by increasing turbulence of the liquid flow in the agitated vessel. Downward pumping mode of the propeller is more advantageous because such a liquid circulation intensifies mixing of the tracer with a bulk of the liquid. Similar results were obtained for two propeller agitators.

The influence of the flow turbulence on the mixing time in the agitated vessel with centrally located single or double propellers is illustrated in Fig. 8. As shown, values of Θ do not practically depend on the Re number within the experimental range. On the other hand, mixing time strongly depends on the number of impellers i, and on the mode of liquid circulation in the vessel. Variation of dimensionless mixing time with Re was approximated by the equation

$$\Theta = n\tau_{\mathrm{m}} = f(Re) = C \qquad (1)$$

The corresponding values of constant C for the different system designs are summarized in Table 2.

When the agitator shaft was situated most eccentrically ($e/R \in \langle 0.43; 0.57\rangle$), the mode of the liquid circulation in the vessel affected the mixing time slightly. The effect of the Re number on Θ for upward pumping is shown in Fig. 9. Similar results were obtained for downward propeller pumping mode.

The results of the mixing time variation with Re within the eccentricity range of $e/R \in \langle 0.43; 0.57\rangle$ were approximated by means of the equation

$$\Theta = CRe^{A} \qquad (2)$$

Values of parameters C and A and mean relative error Δ of fitting the experimental data by eqn (*2*) for selected experimental conditions are given in Table 2.

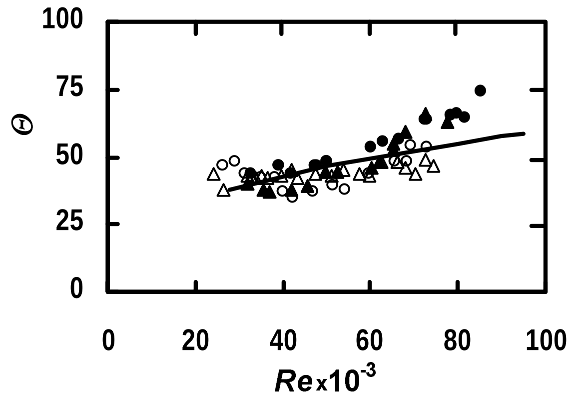

Fig. 9. Influence of the liquid turbulence on the dimensionless mixing time for eccentrically located up- (filled symbols) and down-pumping (empty symbols) single propeller agitator: $e/R = 0.43$ (triangles), $e/R = 0.57$ (circles).

Displacement of the impeller shaft at the eccentric position gives similar effect as the insertion of the baffles in the vessel. In both cases, the tangential flow of the liquid is impeded, but power consumption increases. Therefore, higher agitation energy is responsible for better mixing and the decrease of the mixing time.

SYMBOLS

A	exponent in eqn (*2*)	
C	parameter in eqns (*1*) and (*2*)	
D	inner diameter of the agitated vessel	m
d	diameter of the agitator	m
e	eccentricity of the agitator shaft	m
H	liquid height in the vessel	m
h_1	off-bottom clearance of the lower agitator	m
h_2	off-bottom clearance of the upper agitator	m
i	number of agitators	
n	agitator speed	s^{-1}
R	inner radius of the vessel	m
r	radial coordinate	m
Re	Reynolds number ($= nd^2\rho/\eta$)	
S	pitch of the propeller agitator	m
s	standard deviation	
t	critical value of Student test	
V	total volume of the liquid in the vessel	m^3
V_a	volume of the tracer pulse added	m^3
Z	number of propeller blades	
z	axial coordinate	m
Δ	mean relative error	%
η	dynamic viscosity of the liquid	Pa s
ρ	density of the liquid	kg m^{-3}
ϑ	temperature of the liquid	°C
Θ	dimensionless mixing time ($= n\tau_m$)	
τ	time	s
τ_m	mixing time	s
φ	angular coordinate	°

Subscripts

IP1	injection point 1
IP2	injection point 2
i	i-th measurement
k	final measurement
p	initial measurement

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